Effect of Si content of Hot-Dip Plating on the Interface Structure and Properties of Solid-Liquid Cast and Rolled 6061/Q345 Composite Plate

Xuyuan Zhang[1], Yuandong Li[1,2,*], Tao Ju[1], Guangyu Liu[1], Hongwei Zhou[1], Sheng Wang[1,2], Chi Cao[1,3], Guangli Bi[1,2]

1. State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou, 730050, PR China;
2. Key Laboratory of Non-ferrous Metal Alloys and Processing, Ministry of Education, Lanzhou University of Technology, Lanzhou, 730050, PR China;

3.Wenzhou pump and Valve Engineering Research Institute of Lanzhou University of Technology, Wenzhou 325105, China)

* **Corresponding author:** Yuan-dong Li, e-mail: liyd_lut@163.com, Tel: +86-931-2976795

Abstract: Employing hot-dip coating with Al-XSi alloys, combined with phase diagram analysis and first-principles calculations, the influence of Si elements on the interfacial microstructure, phase composition, and mechanical properties in the cast-rolled 6061/Q345 composite sheets was investigated. Results demonstrated that the addition of Si in the hot-dip coating led to the formation of novel ternary phases, Al-Fe-Si, namely Al3FeSi2, Al9Fe2Si2, and Al0.5Fe3Si0.5, at the aluminum-steel interface, which reduced the brittle phases Al5Fe2 and Al3Fe, thereby enhancing the deformation resistance and toughness of the composite. Compared to the composite sheet with pure Al coating (yielding a tensile strength of 402.4 MPa and shear strength of 51.3 MPa), the maximum values of 438.5 MPa and 120.8 MPa for tensile and shear strengths were achieved with an Al-1%Si (mass fraction) coating, representing increases of 8.9% and 135.4%, respectively. Further increments in the Si content in the hot-dip bath to 7.5% resulted in a decline in both the tensile strength (395.7 MPa) and shear strength (78.6 MPa) of the composite sheet. The tensile and shear strengths exhibited a trend of initially increasing and then decreasing with the rising Si content in the hot-dip coating.

Keywords: Composite board; Solid/liquid casting and rolling; Q345 steel; 6061 aluminum; Interface organization; mechanical property

1 Introduction

Bimetallic composite materials compensate for the shortcomings of single-metal materials in terms of performance, possessing extensive application prospects [1]. However, the formation of brittle intermetallic compounds (IMCs) at the interfaces of these composites significantly deteriorates their mechanical properties, thereby severely restricting their applications [2]. Jiang W [3] prepared aluminum-steel bimetals via composite casting, resulting in an irregular tongue-shaped reaction layer with an average thickness of 30 μm at the aluminum-steel interface. This layer was composed of Fe_2Al_5, $FeAl_3$, Al_8Fe_2Si, and $Al_2Fe_3Si_3$ IMCs. The use of surface modifiers and aluminum plating promoted good interface and metallurgical bonding, increasing the shear strength of the castings by 40% compared to untreated ones.

So far, when preparing composite materials, most studies have focused on the effects of adding elements such as Ni, Cu, Zn. as intermediate layers on the interface organization and properties of composite plates. This study uses aluminum-silicon alloy as an intermediate layer to connect different aluminum and steel materials. On the one hand, it improves the wettability of the interface between aluminum and steel, promotes metallurgical bonding, and enhances the interface bonding strength. On the other hand, by adding Si to suppress the growth of Al-Fe brittle intermetallic compounds, the relationship between the microstructure and mechanical properties of composite plates with different Si contents is analyzed, providing reference for the preparation of aluminum/steel composite plates.

2 Experimental procedure

Alloys of various silicon contents were placed in an SG2-7.5-10 pit-type resistance furnace and heated to 730°C. Refining was conducted with 1% C_2Cl_6, followed by skimming to remove impurities. A 1% cover flux (50% KCL and 50% NaCl) was uniformly sprinkled on the molten surface. The temperature was then adjusted to 720°C for holding. During the holding process, the melt was stirred thoroughly every 10 minutes to ensure the accuracy of the alloy composition. Treated Q345 steel plates were vertically immersed in the 720°C aluminum-silicon alloy melt for immersion coating, with a dipping time of 30 seconds. The immersion coating process was performed with melts of pure Al, Al-0.5%Si, Al-1%Si, Al-2.5%Si, Al-5%Si, and Al-7.5%Si, respectively. Upon completion of the immersion coating, solid-liquid casting rolling was immediately executed.

During hot dipping, the cut 6061 aluminum ingots are placed in another SG2-7.5-10 pit-type resistance furnace and heated to 730°C. 1% (mass fraction) of C_2Cl_6 is added for refining and slag removal. After that, 1% (mass fraction) of cover agent (50% KCL and 50% NaCl) is uniformly sprinkled on the surface of the melt, and the temperature is adjusted to 680°C for holding. The roll gap of the rolling mill is set to 4mm, and the 680°C 6061 aluminum liquid is quantitatively poured onto the Q345 substrate treated by hot dipping. The rolling speed is 42mm/s, and the maximum rolling force is 170kN. After starting the rolling mill, the two alloys are sent between the two rolls for solid/liquid casting and rolling, followed by air cooling.

3 Result and discussion

As depicted in Fig 1, the schematic illustration of phase formation in the aluminum-iron composite bonding layer ， with the progression of diffusion (Fig 1b), intermetallic

and Fe atoms enter the intermediate layer from both sides. Due to the continuous supply of energy from the 6061 melt, the bonding layer has a slower cooling rate, allowing for sufficient mixing of Al, Fe, and Si elements during the cooling process. with the addition of Si atoms, the Si atoms tend to segregate in the intermediate layer, hindering the diffusion of Fe and Al atoms (Fig 1d). Additionally, the Si atoms can occupy vacancies in the Al_5Fe_2 phase, inhibiting the growth of the Al_5Fe_2 phase (Fig 1e, Fig 2). Furthermore, as shown, when the Si content increases (exceeding the solid solubility of Si in Al_5Fe_2), new Al-Fe-Si phases (Al_3FeSi_2, $Al_9Fe_2Si_2$, and $Al_{0.5}Fe_3Si_{0.5}$) are formed to suppress the growth of the original Al-Fe intermetallic compounds, resulting in a smoother appearance on the steel side and a reduction in the thickness of the intermediate layer (Fig 1f).

When the C-axis of the Al_5Fe_2 phase is oriented at 90° to the initial aluminum-steel interface, it exhibits the fastest growth rate, suppressing the growth at other angles, as demonstrated in Fig 1b and c. Al_5Fe_2 is the predominant phase in the aluminum/steel intermetallic compounds, while the thermodynamically most stable Al_3Fe phase constitutes a relatively small proportion in the actual phase composition, which deviates significantly from thermodynamic predictions. Research indicates that the growth of intermetallic compounds is not solely governed by thermodynamic driving forces but also involves the state of diffusing atoms in dissimilar metals and interface conditions.

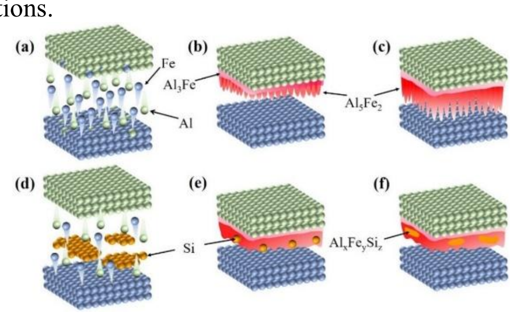

Fig. 1 Diagram of the formation of the interlayer phase
(a) Diffusion of Al and Fe atoms; (b) Initial stage of interlayer phase formation; (c) Termination stage of interlayer phase formation;(d) Si atom bias and enrichment; (e) Si atom occupying vacancies; (f) formation of AlxFeySiz phase

compounds will initially appear on the aluminum side. The thermodynamically most stable Al_3Fe phase is the first to emerge. As aluminum atoms diffuse further, the Al_5Fe_2 phase starts to grow at the interface between the Al3Fe phase and the Fe(Al) solid solution. The Al_5Fe_2 phase has an orthorhombic lattice structure with a high concentration of vacancies (30%) along the C-axis, as shown in Fig 2 [4]. During the bonding process of al/steel composite materials with an Al-Si alloy intermediate layer, the Al-Si intermediate layer that is first in contact with the molten 6061 aluminum liquid melts first. Subsequently, Al atoms

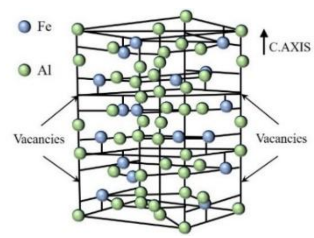

Fig. 2 Diagrammatic representation of the structure of the Al5Fe2 phase[4]

4 Conclusion

(1) The mechanical properties of the composite plate containing Si elements in the middle layer are higher than those of the composite plate without Si elements.

(2) The introduction of Si element in the hot-dip plating solution leads to the formation of new phases such as $Al_9Fe_2Si_2$ phase, Al_3FeSi_2 phase and $Al_{0.5}Fe_3Si_{0.5}$ phase at the composite interface, which changes the phase composition at the interface and improves the mechanical properties of the composite plate.

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